The Making of India's First Short-Length Sustained Foucault Pendulum and the New Design

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Abstract

Because of their elegant looks, emotive appeal and profound educational implications, many shorter and improved versions of the Foucault pendulum have found their ways into the hallways of famous government buildings, central lobbies of universities and the foyers of some of the world's best science museums. However, none was to be found in India till very recently. The article describes the first successful Indian attempt in building a short-length sustained Foucault pendulum at the Central Research & Training Laboratory of the National Council of Science Museums (NCSM).

Construction of a Foucault pendulum and its successful installation poses many daunting problems. Its performance is delicately dependent on various factors; some are intrinsic parameters of the design and some are due to external influences. Different designs have been tried world-over for better performance and long life of the pendulum. The first Indian effort succeeded in incorporating novel features in the pendulum's suspension system resulting in enhanced accuracy. The new design also got a patent cover for its innovative features.

Introduction

The earth rotates about its polar axis once in nearly 24 hours, resulting in the cyclic occurrence of days followed by nights. It is a phenomenon so matter of fact that we hardly demand a direct experimental proof for this celestial clockwork. However, can a terrestrial experiment be designed for a direct & quantitative proof of the planet's rotational motion?

Fig. 1. Leon Foucault (1819-1866).

In 1851, a wonderfully simple but ingenious experiment carried out by the famous French physicist Leon Foucault (Fig. 1), provided the first direct proof of the rotational motion of the earth. His celebrated pendulum experiment is held in reverence by physicists and astronomers as one of the brilliant experiments of all time. Successive pendulum experiments that replicated or improved upon Foucault's pioneering efforts came to be known as 'Foucault Pendulums' after the great inventor's name.

Although Leon Foucault's original experiment was a novel work, the set-up he used was not suitable for continuous observation and the results obtained lacked in quantitative accuracy.

Foucault Pendulum: Historical Background

The Foucault pendulum was invented by accident, and any description of a Foucault pendulum is incomplete without a brief anecdotal reference to this fortunate 'accident'.

In 1848 Leon Foucault was setting up a long, skinny metal rod in his lathe. He accidentally 'twanged' it, and the end of the piece of metal proceeded to go up-and-down. The rod continued to vibrate in the same plane while the chuck rotated its fixed end. This set Leon Foucault thinking. He suspended a short pendulum from the chuck of a vertical drill press, set the pendulum oscillating, and then started the drill press. Once again, the pendulum kept swinging in its original plane, and ignored the fact that its mounting point was rotating. That very moment Foucault came to know for sure he had a system that maintained its orientation even in a rotating frame.

He went on to construct a 2 metre-long pendulum with a 5 kilogram ball in his workshop and set it in motion. Before the amplitude of its swing died away, which it did very quickly, he could see that the weight on the end of the pendulum appeared to rotate clockwise very slightly. He knew that observation over a longer period was necessary to be sure of the apparent clockwise rotation of the pendulum's plane of oscillation. He then built a second pendulum with an 11-metre long wire and put it in the Paris Observatory for observation. It too rotated clockwise.

Foucault had no doubt left in his mind that a sufficiently long pendulum would be able to demonstrate the rotational motion of the earth clearly. And he decided to construct a really long one.

A 62 pound cannon ball held by a 200 feet long piano wire constituted his pendulum. The fact that a long pendulum would sustain its oscillation for longer and that a heavy one would be more immune to external disturbances led Foucault to design such a huge pendulum, which required nothing less than the dome of Pantheon to be hung from (Fig. 2). He also took

Fig. 2. The Pantheon in Paris

great care to make sure that the wire was perfectly symmetrical in its metallurgy. When the pendulum was hung, a sand bed was made over an area just below it, and a stylus was touched the sand. For setting the pendulum in motion, the bob was pulled to one side and tied in place with a thread. When the system settled, the thread was burned. The pendulum made true sweeps, to and fro, while the stylus traced straight lines on the sand bed. The pattern gradually grew in a clockwise direction, and at the end of an hour the line had turned 11 degrees 18 minutes. The only reason was, Foucault argued, the earth had turned beneath the pendulum while the pendulum's plane of swing simply refused to do so. He was, as he put it later, was seeing the earth spinning around.

The success of the experiment caught the fancy of nineteenth century Europe and was repeated with varying degree of success at Cologne, Reims, Amiens, St. Jacques and elsewhere where towers of great heights were available for doing the experiment.

Many experimentalists have since then developed shorter and improved versions of the Foucault pendulum for sustained operation and greater accuracy of performance in respect of their ability to measure the rotational rate of the earth. These pendulums, because of their elegant looks and profound emotive & educational implications, have easily found ways into the hallways of famous government buildings, central lobbies of universities and the foyers of some of the world's best science museums. Famous examples are the UN building in NY and the Deutches Museum in Munich. However, while most of these experiments have been designed and displayed in the western world, none has so far been reported as a successful Indian venture prior to the one this article describes.

Genesis of the First Indian Attempt

The first Indian attempt to develop a self-sustained Foucault pendulum had to wait, for reasons quite inexplicable, until 1991 when a request for indigenously developing one was received by Dr. Saroj Ghose, the then Director General of the National Council of Science Museums (NCSM) from none other than the noted astrophysicist, Professor J V Narlikar. He was then finalizing the architectural plan for his new institute, the Inter-University Centre for Astronomy and Astrophysics in Pune. He wanted to have a performing Foucault pendulum to adorn the central lobby of the new building that was to carry the hallmark of a Charles Correa design. What could have signified the objective of an institute on astronomy and astrophysics better than a shining sphere of metal, elegantly hung by a long wire and ceaselessly swinging back and forth over the central court while changing its plane of swing continuously? The system could serve as a testimony to the spin of the earth and hence was an apt choice that could set the underlying tone of the institute – to demystify the heavens.

The NCSM accepted Prof. Narlikar's request, and with this the seed of India's first Foucault pendulum was sown.

Building up the Theoretical Framework

A team under the leadership of Mr. Ingit Mukherjee, the then director of NCSM's Central Research & Training Laboratory (CRTL) at Salt Lake, Kolkata was formed which was made responsible for the design and development of the pendulum. Being a member of the team, the author of this article was witness to the painstaking and often frustrating efforts that underwrote the making of the first Foucault pendulum in India.

We began with no prior knowledge about the design considerations for a short-length driven Foucault pendulum system. Hence we first decided to study available literature to obtain a preliminary parametric guideline as to how to proceed to actually construct a Foucault pendulum. The questions we asked ourselves were:

What would be the theoretical value of the earth's rotational rate at Kolkata where the experiment was to be conducted? How much would the pendulum's apparent rate of rotation vary from the theoretical value due to design parameters? What environmental factors would influence the performance of the pendulum? What were the crucial design considerations? How much error would be considered acceptable?

The result of our studies was tabulated, which provided a broad theoretical framework and served as the launching pad for our work.

Physics of the Foucault Pendulum

Foucault pendulums demonstrate earth's rotation while normal pendulums do not. Why?

Anything that is fixed to the earth by either mechanical means or by the pull of gravity is also carried along with its rotational motion. In order that earth's rotation is detected by a terrestrial experiment, one needs to have a system which has some measurable parameter that remains invariant under the rotation of the earth. This would mean that the experiment must use a set-up, which despite being held in the earth frame, is capable of effectively freeing itself from it. By definition, a simple pendulum does accomplish the task once it is set swinging freely. Let us examine why this happens.

In order to change the simple pendulum's plane of swing, a torque is needed to act on the plane about its support. This would require two things: an external force having a non-zero component at right angle to the plane of oscillation, and a position away from its axis on the pendulum's plane where the external force could be applied. Both these requirements are not met in the case of an ideal simple pendulum. Considering the suspending wire to be perfectly flexible, there can be no moment due to bending of the wire. Also, since there is no friction at the support, no moment due to frictional forces exist about the support. Thus a swinging pendulum is acted upon by only two forces, namely, the tension of the string and the gravity force (neglecting air friction and other external noise). None of these two forces has any moment about the axis of the pendulum. Moreover, since an ideal simple pendulum is held by a single point support, there exists no point on its plane away from the axis where an external force, even if it existed, could be applied to yield a non-zero moment about the axis. Hence it is easy to appreciate why the plane of oscillation of an idealized simple pendulum would become invariant under the rotation of its support.

If a pendulum is designed to effectively behave as an ideal simple pendulum by removing the possibility of asymmetric forces affecting its motion, a Foucault pendulum will have resulted. For a Foucault pendulum designer, understanding how asymmetric forces could creep in the system is of paramount significance for being able to deal with it during both design and fabrication stages.

If the internal structure of the wire is such that it cannot bend with equal ease in all radial directions in its cross-section, the plane of swing of the pendulum would seek a preferred direction in which the wire can bend with maximum ease, and would thus be carried by the rotating earth instead of being fixed in space. Also, the manner in which a practical pendulum is held is of immense importance because an asymmetric support structure may lead to a preferential or a fixed plane of swing. An asymmetric support is one that does not hold the wire equally rigidly from all sides, and thus introduces unequal radial flexibility for the wire at the support point. Such departures from ideal conditions may introduce varying periodicity in different planes of oscillation, which eventually makes the pendulum execute elliptical motion instead of true sweeps.

Overcoming these limitations for a practical pendulum is a daunting task. To make a practical design mimic the attributes of a theoretical pendulum is a challenge even to the accomplished engineers – a reason why we make pendulums everywhere, but Foucault pendulums very rarely.

Apparent Turning Rate: Latitudinal Variation

A Foucault pendulum's apparent turning rate at any place on the earth's surface would necessarily be equal in magnitude and opposite in sense to the angular rotation of the earth about the vertical at that place. We derived a general expression for the earth's rotational rate about the vertical at any latitude using the geometrical construction given in Fig. 3:

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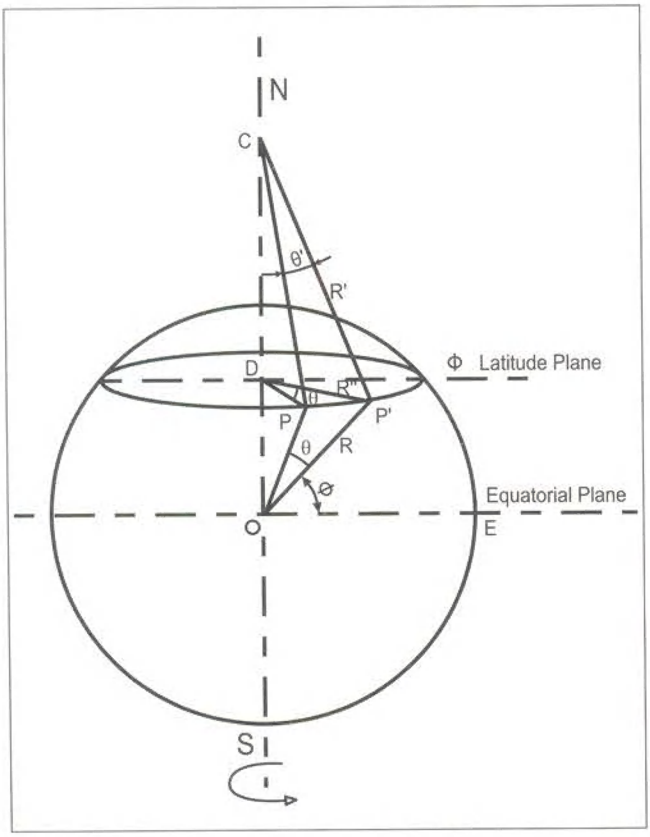

Fig. 3.

f : Latitude angle of the place P, P'...

q : Angle swept in the latitude plane of P, P' by the displacement of point P to P' due to earth's diurnal rotation.

q' : Angle traced by the tangent plane CP by the displacement of P to P'due to the rotation of earth. [This is the angle which the pendulum's plane of oscillation would appear to rotate with respect to the observer at P, P' over time 't' during which P is displaced to P']

From the diagram:

i) Đ POE = Đ P'OE = f (latitude at PP') = Đ OCP = Đ OCP';

ii) OP = OP' - R, radius of Earth;

iii) DP = DP' = R'',radius of latitude circle (=R cos$f$);

iv) CP = CP' =R', slant height of tangent envelope cone.

$\varnothing$: Latitude angle of the place P, P'...

θ : Angle swept in the latitude plane of P, P' by the displacement of point P to P' due to earth's diurnal rotation.

θ' :Angle traced by the tangent plane CP by the displacement of P to P' due to the rotation of the earth. [This is the angle which the pendulum's plane of oscillation would appear to rotate with respect to the observer at P, P' over time 't' during which P is displaced to P'].

From the diagram:

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ii) OP = OP' = R, radius of Earth;

iii) DP = DP' = R'', radius of latitude circle (=R cos$\varnothing$);

iv) CP = CP' = R', slant height of tangent envelope cone.

Derivation:

Length of arc PP' = R'' θ = R' θ' (permitted for small θ') .... (1)

In Δ DPO, $\angle$OPD = $\varnothing$, $\angle$D = 90° and hence $\frac{R''}{R}$ = Cos $\varnothing$, or R'' = R. Cos $\varnothing$ ....(2)

Putting **(2)** in **(1)**, we get $\theta' = \left|\frac{RCos\varnothing}{R'}\right| \theta$ or

$\frac{d\theta}{dt} = \left|\frac{RCos\varnothing}{R'}\right| \frac{d\theta}{dt}$ ....(3)

In Δ CPO, Tan $\varnothing$ = $\frac{R}{R'}$; or R = R' Tan $\varnothing$.........(4)

Substituting **(4)** in **(3)**, one gets $\frac{d\theta'}{dt}$ = (Tan $\varnothing$ Cos$\varnothing$) $\frac{d\theta}{dt}$;

or $\frac{d\theta'}{dt}$ = Sin$\varnothing$ $\frac{d\theta}{dt}$ ....(5),

which gives the general expression for the rotational rate at any place having latitude angle $\varnothing$. Earth's rotational rate $\frac{d\theta}{dt}$ about its polar axis being equal to 15°/hour, an expression for the Foucault pendulum's apparent rate of rotation at any latitude $\varnothing$ is obtained from equation (5):

***w* ($\varnothing$) = 15° x sin $\varnothing$ per hour** ....(6) (sense being clockwise in northern hemisphere and anticlockwise in the southern hemisphere).

One could also arrive at (6) from a physical consideration of the system (Fig. 4).

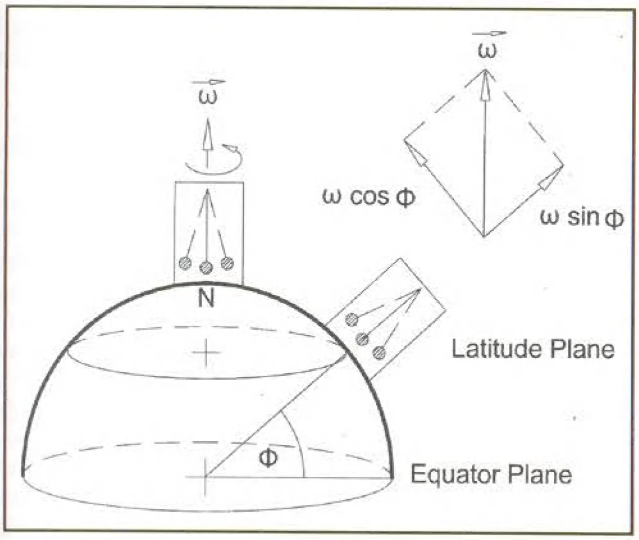

Fig. 4.

If $\vec{w}$ denotes the angular velocity vector of the earth about its polar axis at the North Pole, then $|\vec{w}|$ 15°/ hour (anticlockwise). At any latitude $\emptyset$, the projection of $\vec{w}$ on the local vertical is $\vec{w}(\emptyset) = \vec{w}\ \sin\emptyset$. Here a Foucault pendulum's apparent rotation is $|\vec{w}|\sin\emptyset = (15°\mathrm{x}\sin\emptyset)$/ hour (clockwise). In terms of the time $\mathbf{T}'$ taken by the pendulum to rotate through 360°, equation (6) above can be rewritten as:

$T' = \frac{360°}{15°\mathrm{x}\sin\emptyset}$ hrs $= \frac{T}{\sin\emptyset}$ hrs .....(7), where T is the period of earth's diurnal rotation.

<u>At the poles</u>: $\emptyset = 90°$, $w(\emptyset) = 15°$ (from equation 6), or the rate of apparent angular rotation of a Foucault pendulum at the poles will be maximum and equal in magnitude to the Earth's rate of rotation about its polar axis.

<u>At the equator:</u> $\emptyset = 0°$, therefore $w(\emptyset) = 0$ (from equation 6), which means a Foucault pendulum installed at the equator will not show any apparent rotation of its plane but instead will be carried along by rotating earth.

Effect of Design Parameters on Turning Rate

If 'a' and 'l' denote the amplitude and the length of the pendulum respectively, then it can be theoretically derived that equation (7) above gets modified as

$$T' = \frac{T}{Sin\,\emptyset}\,[1-(3a^2/8\,l^2)] \text{....... (8)}$$

However, another modification in the above expression becomes necessary due to the constructional parameters of the 'Charron Ring', a very important component of the Foucault pendulum system that will be discussed later. Finally we have the following modified equation:

$$T' = \frac{T}{Sin\,\emptyset}\,[1-(3a^2/8\,l^2)-(4d/\pi\,a)] \text{....... (9)}$$

where, a = amplitude of swing; l = length of the pendulum; d = annular spacing at the Charron ring.

Equation (9), therefore, provides the theoretical benchmark for judging the performance of our proposed pendulum. This, however, excludes possible perturbations to the pendulum's motion due to external noise like vibration of support structure, air current or presence of strong magnetic field etc.

Our Failed Experiments

With the necessary theoretical background in place, we were in a position to actually start the design and fabrication work in the mechanical workshop of the Central Research and Training Laboratory at Salt Lake, Kolkata. The workshop had an area with double floor height, which could accommodate a length of about 20 feet that we thought was a workable size for our first attempt.

Three subsystems are important for any pendulum set up:

a) pendulum itself (wire and the heavy bob)
b) suspension or support structure
c) driver unit

In addition, precise alignment of the subsystems along a vertical axis is crucially important. The suspension point, the suspension wire, the centre of gravity of the bob, the centre of the driving force field- all must lie along the same vertical line.

<u>First Attempt</u>

Initially we used for the pendulum bob an iron ball of about 100 mm in diameter and approximately 4 kilos in weight (We had the ball in our workshop and used it for the 'shot put' event during our annual sports). It was hung by an 18 feet long, single strand 18 swg GI wire of the common type.

For the suspension unit, we turned a 50 mm long piece of a 62 mm dia brass rod in the lathe and drilled a hole

through it which could just accommodate the diameter of the wire without any visible slackness. We tapered off one end of the wire and passed it through the hole forcibly until about a couple of inches of it protruded out at the opposite end. The tapered portion was cut off and a lump of metal was then brazed at the tip such that the wire would not slip back through the hole under the weight of the metal attached to the other end of the wire by means of a hook welded to it. The brass piece holding the upper end of the wire was screwed to a 6 mm thick mild steel plate, which in turn was fixed to the ceiling.

For the driving unit, we used an electromagnetic driving system, which basically consisted of an electromagnet, and an electronic control circuit that ensured that the electromagnet was energized only when a magnetic or a conducting body passed over its centre. All the three subsystems were aligned to the best of our ability and the set up was ready for a trial run.

For checking the expected rotational motion of the pendulum, a reference court with graduation marks at every 5^0 interval was placed centrally just below the ball. A hole that easily allowed the pole piece of the electromagnet was made exactly at the centre of the court made of plywood. The electromagnet was kept below the court in such a way that its pole piece just flushed with the surface of the court. For starting the pendulum, we followed a procedure widely prescribed in the literature. The metal ball was pulled to one side and was held in this position with the help of a cotton thread that tied the ball to a fixed post. When the system became still, the thread was burned. The ball started moving to and fro passing over the central pole piece.

The pendulum appeared to execute, to our delight, true sweeps, but only initially. Within about ten minutes time its amplitude decreased visibly and the pendulum started to move elliptically. The minor axis of the ellipse grew quickly resulting in almost a circular motion about the central pole piece and ultimately the pendulum stopped.

Second Attempt

Keeping all other components intact, we replaced the iron bob with one made of brass and then glued to its bottom a ceramic magnet of one-inch diameter. A circular undercut was made in the lathe for properly locating the ceramic magnet at the exact centre of the bottommost part of the pendulum such that the suspension wire, the centre of the bob, the centre of the ceramic magnet and that of the electromagnet – all fell in the same vertical axis. We then started the pendulum all over again and waited with baited breath.

The oscillations showed no sign of dying down even after 15 minutes, and to our delight, its plane also visibly moved away from the direction in which we had left it alone. Taking reference of the graduated court over which the pendulum moved, we started noting down the turning rate every 15 minutes. Our readings gave a rate that was higher than the theoretical value of 5.8^0 per hour calculated for Calcutta's latitude. The observation was disturbing, but we decided to wait and watch. Further readings during the next couple of hours brought new surprises - the pendulum turned increasingly faster and also performed ellipses instead of linear sweeps. We left the pendulum 'on' overnight. At 10 o'clock next morning when we resumed our observation, a kind of shock greeted us. Even after almost 16 hours, it has made a ground of only about 20 degrees, lagging behind the theoretical value by a whopping 76 degrees. While we started thinking about the possible reasons for the failure, we allowed the pendulum to run as long as it could, hoping to at least assure ourselves that the driver system worked.

But more shocks were in the offing. The pendulum's plane refused to shift from where it had been at 10 a.m. We had no idea of what had happened between 6 p.m. in the previous evening when it was tuning faster than expected, and 10 a.m. that morning when it stopped turning altogether, although it continued to swing in this fixed direction maintaining constant amplitude.

Apprehending that the alignment of the suspension unit with respect to the vertical at the point of suspension might not have been proper, we stopped the pendulum and went up to the ceiling, and realigned the suspension unit with as much precision as we could. The centering of the electromagnet and the ceramic magnet at the bottom of the bob was rechecked and the pendulum was then restarted in a direction different from the one in which it got fixed. The plane apparently shifted clockwise again, its rate this time slowing down with time in contrast to the previous experience, and after about 5 hours of strenuous journey in the same direction, it gave up. The pendulum stopped changing its plane of swing and remained fixed in a particular direction different from the earlier case. In order to find out the preferred sectors over which the pendulum turned either faster or slower, we restarted its swing in a direction a few degrees further away in the clockwise sense hoping to ease the pendulum out of the preferred direction in which it was trapped. We retired for the night and came back next morning hoping to see the pendulum leave a trail of why it had been behaving so mysteriously.

But the pendulum was gone. Together with the entire length of the wire coiled around in inanimate stillness, the heavy bob laid crestfallen on the edge of the court in deadly silence. We too missed a few beats at the premature demise of our pendulum.

The wire snapped just below the brass holder of the suspension assembly. We now had an additional jinx to get level with. Survival of the suspension wire for a considerable period was a fundamental prerequisite that must be ensured if we were to meet with any possible success in future.

Learning Points

We had these challenges to meet:

* Preventing premature snapping of the wire and ensuring long life of the pendulum.
* Redesigning the suspension assembly to ensure not only a long life for the wire but also to prevent the pendulum from seeking preferred direction. Because if it did, the wire would undergo continuous flexing along a fixed line in its cross section and will eventually snap.
* Arresting or eliminating the tendency to perform ellipses instead of linear oscillations.

We decided to experiment with various types of stainless and spring steel wires available in the market,

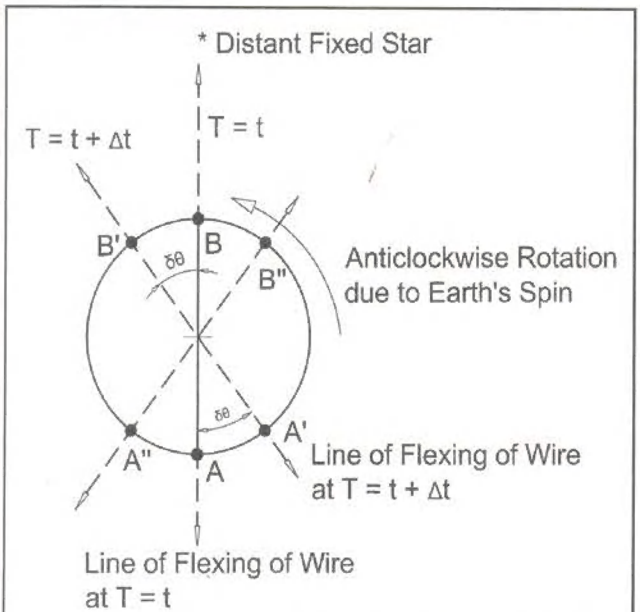

Fig. 5. Cross-sectional view of wire.

although we knew that no wire would be able to sustain millions of flexing operations in one direction. Here lies the importance of prohibiting the pendulum from seeking a preferred direction for its plane. I am tempted to dwell a little more on this issue of crucial importance and would seek the reader's attention to the explanatory illustration (Fig. 5).

Consider a cross-section of the wire at the point of suspension. Suppose at time T = t, the wire flexes along the line *AB* pointing to a fixed direction in space. An infinitesimally small instant later at t = t + δ t, the wire turns anticlockwise along with the earth by say, $\delta\theta$ moving the line *AB* to *A'B'*. Now for a Foucault pendulum, the plane of swing would remain invariant under the earth's rotation, which means that at t + δ t, a new line *A''B''* would be brought by the rotating earth along the spatial direction pointing to the same fixed star. And again after an interval δ t, another new line in the pendulum's cross-section would fall along the plane of swing.

In Calcutta the pendulum would take about two and a half days to make a complete rotation. Therefore if our experimental system performed as a Foucault pendulum, the wire would flex along any particular direction in its cross-section only once in two and a half days. On the other hand, if the pendulum's plane of swing would get fixed with respect to the earth frame instead of the space frame, then any particular line of the wire's cross-section would flex about 100,000 times during the same time. That is to say that the life of the wire would be 100,000 times more if it supported a pendulum performing as a Foucault pendulum than if it worked as a normal pendulum.

Relooking at Some Crucial Features

Suspension System

The above analysis at once convinced us to focus our attention more on the suspension system, which mostly determined whether the pendulum would be able to oscillate equally freely in all possible directions. Achieving an absolutely symmetric rigid support was the key factor for success.

But we honestly had no idea how to proceed further. We surveyed available technical literature on the subject and get hold of a few that reported the suspension unit in some detail.

Of all the successful designs, the one developed by Philips for supporting the pendulum at the entrance hall of the UN Headquarters in New York was the most reported.

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The central features of their system were: the use of a universal joint for ensuring equal radial flexibility of the wire it held. The next well known system we came across used a four-jawed chuck for holding the wire equally rigidly from all sides. Among the other less known, the double knife-edge supports were reported to have worked if constructed perfectly. We chose to go for the incorporation of a universal joint in our new system.

The Problem with Elliptical Motions and the Importance of Charron Ring

It was essential to incorporate a system in our future design which would arrest the pendulum's tendency to undergo elliptical oscillations. Otherwise the pendulum's plane of swing would undergo precession on its own, and hence would make precession due to earth's rotation immeasurable.

We undertook elaborate theoretical exercises to get to the root cause of the observed elliptical motions. On a simplistic note, it might be said that ellipses instead of straight-line motion for a pendulum would occur if it had different periodicity of swing in different directions, imparted by imperfections in the structure of the wire, unequal rigidity and lack of absolute symmetry in the support, perturbations due to external influences like air current and also presence of magnets or ferromagnetic substances in the vicinity of the bob (because it had a permanent magnet at the bottom) or near the electromagnetic driver unit.

We knew that complete elimination of the above reasons for elliptical motion was not possible and hence we could only attempt a curative measure and not a preventive one. Fortunately, we came across the so called 'Charron Ring' system used by Philips for its pendulum at the UN building in NY, which had a carefully centred metal ring just below the support structure through which the wire passed and rubbed against twice in each swing.

Named in honor of M.F.Charron, a French physicist who first derived it, the Charron system of suspension is a simple method of overcoming the "ellipsing" problem. The following diagram illustrates the system (Fig. 6a & 6b).

At a distance l' below the point of suspension A (see figure 6a) Charron fixed a metal ring B having an internal diameter slightly larger than the thickness of the pendulum wire, leaving an annular spacing of d. As soon as the deflection of the bob exceeds the value $\frac{ld}{l'}$, the wire touches the ring and the point of contact then functions as the "point of suspension". The consequence is that the minor axis of an elliptical orbit which may have been forming is rapidly diminished. With reference to the figure 6b below, this can be roughly explained as follows.

Assuming that the wire, as long as it does not touch the ring, is straight, it will describe at the level of the ring an ellipse geometrically similar to the elliptical orbit of the bob reduced in the ratio $\frac{l'}{l}$.

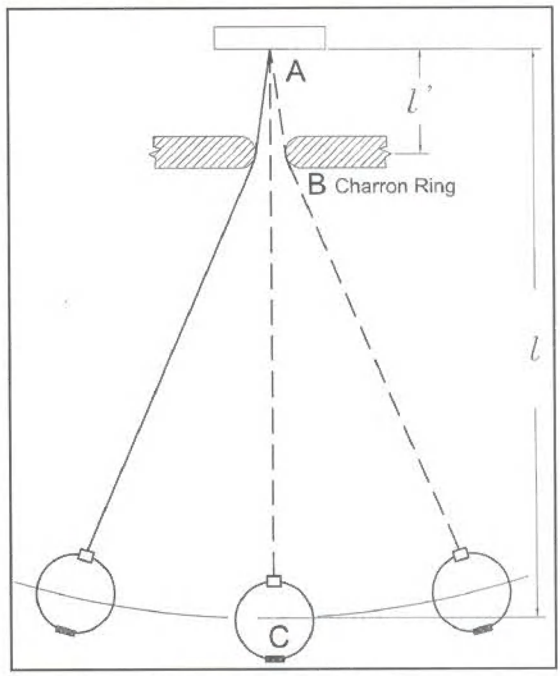

Fig. 6a. Charron's suspension system.

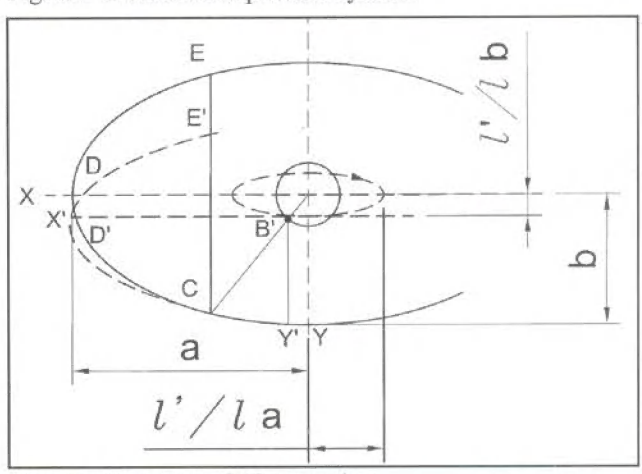

Fig. 6b. Function of Charron ring.

We see, then, that the amplitude in the Y direction at the beginning of the following half-swing has been reduced by the distance EE', which is approximately equal to $\frac{2bl'}{l}$. The relative reduction for each full swing amounts to $\frac{\Delta b}{b} = \frac{4l'}{l}$, where Δb = the decrement in the minor axis of the ellipse due to Charron ring. It has been tacitly assumed in the foregoing that while the bob describes the orbit $CD'E'$ the wire stays pressed against the ring at point B'. As a rule the contact friction will not be sufficient for this to occur. In reality, therefore, $\frac{\Delta b}{b}$ is smaller than calculated here, but this does not alter the fact that the mounting of the ring is a very effective means of combating the elliptical motion. Charron deduced that the use of this construction would slightly shorten the expected period of rotation of the pendulum's plane given by the factor $(4d/\pi a)$ in Equation (9) stated earlier.

Elliptical motion in a freely swinging pendulum is accompanied by an intrinsic precession of angular velocity $\omega = \frac{3A}{4l^2T}$, where A is the area of the ellipse (path of the bob projected onto the horizontal plane), l is the length of the pendulum, and T is the period. The sense of the precession being the same as that of the elliptical motion, the effect is strong: for example, for a pendulum of length 2 m and amplitude (centre to extremity) 0.2 m, the intrinsic precession rate will be equal to the Foucault turning rate (at 40° latitude) if the minor diameter of the ellipse is 2.2 mm. For the error to within 20%, which many consider tolerable, it would have to be less than half a millimetre, an amount scarcely perceptible to the eye.

Thus we found that the problem of the precession due to elliptical motion rapidly become more serious as the length of a Foucault pendulum is decreased to about a few metres, roughly the kind of length we were experimenting with. Hence the use of a perfectly designed Charron ring became absolutely necessary for us.

Modified Experiment That Also Failed

Our next experimental set-up was a more enlightened effort aiming to make use of all the knowledge we gathered in the meanwhile. We changed the suspension system to incorporate a universal joint (of the type readily available in the market), put a Charron ring (as a separate unit) a little below the point of suspension of the wire, used a length of a new and fairly straight 18 swg s.s wire. We used the earlier driver unit because it worked well. And thus, after almost a period of two months, our next set-up was put on test run at the same site. The swing attained and sustained its target amplitude sweeping over the court back and forth ceaselessly in what looked like true oscillations. In fact the pendulum did everything right except doing what it was made for – its plane remained as flat-footed as a stubborn child on his way to school.

I could hardly accept the construction would have gone wrong and instead would vouch that the alignment of the different subsystems viz. the suspension assembly including the universal pivot, the Charron ring, the bob with the magnet and the electromagnet, might not have been proper and required readjustment. I went up to the ceiling and watched carefully how the universal joint was doing. I noticed that the pendulum's fixed direction of oscillation fell in line with the free direction of motion corresponding to the bottom pair of bearings in the universal joint. It occurred to me that the universal support system for the pendulum was not as free in other intermediate directions as it was in the two mutually perpendicular axes in which its two pairs of bearings were mounted. In order to check my suspicion, I stopped the pendulum and restarted it in an intermediate direction between the two free axes of the bearings. The result was revealing. The pendulum's plane of swing started moving in the right direction, developed narrow ellipses whose temporal growth lacked wide variation in the dimension of the minor axis (as was seen in earlier attempts), and ultimately stopped shifting any further as it reached the plane in which one of the pair of bearings of the universal support structure was mounted.

Analysis of Result

We concluded that the commercially available universal joint used in the suspension structure did not allow the pendulum equal flexibility in all radial directions and the pendulum could move with maximum ease only in the two mutually perpendicular axes of its two pairs of bearings.

It was also clear that although Charron ring was effective, its accurate centering with respect to the swing was crucial and this was very difficult to achieve without integrating the Charron ring with the suspension structure itself.

A series of experiments each trying to improve on the previously failed ones followed spanning over a frustratingly long period of time. It was about a year we had been into it, and yet success eluded us. But we would often take solace from R. Stuart Mackay who in his celebrated article in the American Journal of Physics, [21,180(1953)] wrote on the difficulty in designing and assembling of a Foucault pendulum,

"Finally it must be stated that the task of setting up a Foucault pendulum is a tedious one. One must achieve absolute symmetry if it is to turn at the correct rate, rather than seeking out a preferred direction. Besides the drive mechanism, special care must also be given to the clamping of the wire whose bending constitutes the pivot. Absolute perfection can be marred even by the crystal structure of the supporting steel wire."

A Novel Idea & the New Design

We held intensive brainstorming sessions on how to fabricate an isotropic and uniformly rigid support, which while snugly holding the wire, would allow it to flex in all possible directions without being either slack or extra-tight along any one of them. Also the material of the support was to be such that it would withstand millions of abrasive contacts with the stainless steel wire rubbing against its surface twice in each cycle. Simultaneously, the wire also required protection from the abrasive contact with the lower end of its holder against which it lapped with great force twice in each cycle of swing.

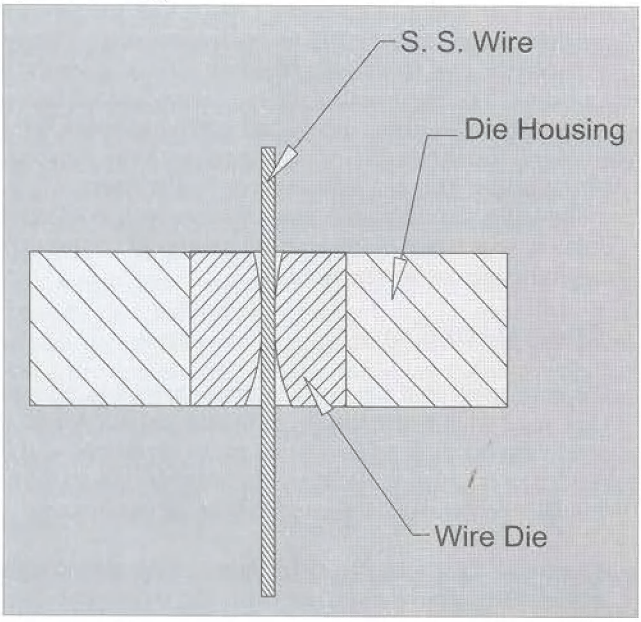

Fig. 7. Sectional view of a typical wire drawing die.

Mr. Mukherjee suggested that we might try a typical wire-drawing die which is used industrially to draw wires of the same gauge as the one we intended to use for our new set-up. The typical structure of a die (Fig. 7) with its smoothly flared end and the uniformly narrow neck was indeed an ideal possibility for holding the wire the way it was required for our purpose. Being made of tungsten-carbide alloy, the die was materially very tough and could easily withstand the forces of wear and tear. The smooth flaring at one side of the die could provide the safest contour against which the pendulum's wire would lap at the two extremities of its swing.

It took us some time to find out the source from where we could procure a Die that were meant for drawing a 16 swg wire, the size we decided to work with henceforth.

We eventually got hold of one that looked perfect and immediately got down to actually designing the new suspension system for our pendulum. The proposed new design was to be built based on:

* holding the wire by means of an actual wire-drawing die,

* the Charron ring was to become an integral part of the suspension system to avoid centering difficulties,

* inherent structural asymmetry of the wire (which normally is sold in coils) was to be taken care of.

After much thought and deliberations we came up with a new design of the pendulum (Fig. 8a & 8b).

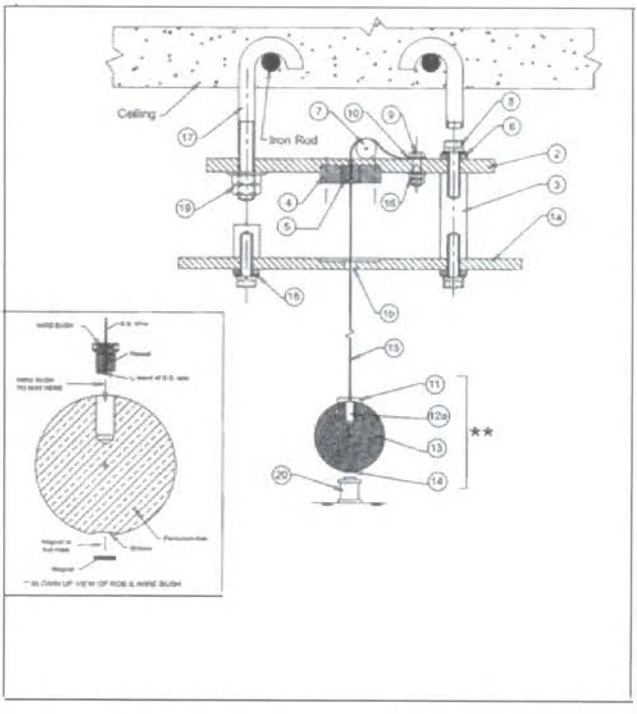

Fig. 8a. The New Pendulum – Assembly Drawing.

Part No.	Description
1a.	Charron Ring Plate
1b.	Charron Ring
2.	Mounting Plate
3.	Dowel Spacer
4.	Brass Housing
5.	Wire Die
6.	Cup Washer
7.	Aluminium Roller
8.	Allen Bolt
9.	Anchor Bolt
10.	Anchor Washer
11.	Fastener Bolt
12a.	Anvil
12b.	Blown up view of BOB
13.	Pendulum BOB
14.	Disc Magnet
15.	S. S. Wire
16.	Lock Unit
17.	Foundation Bolt
18.	Spring Washer
19.	M-12.7(TVS)Nut
20.	Driver Coil

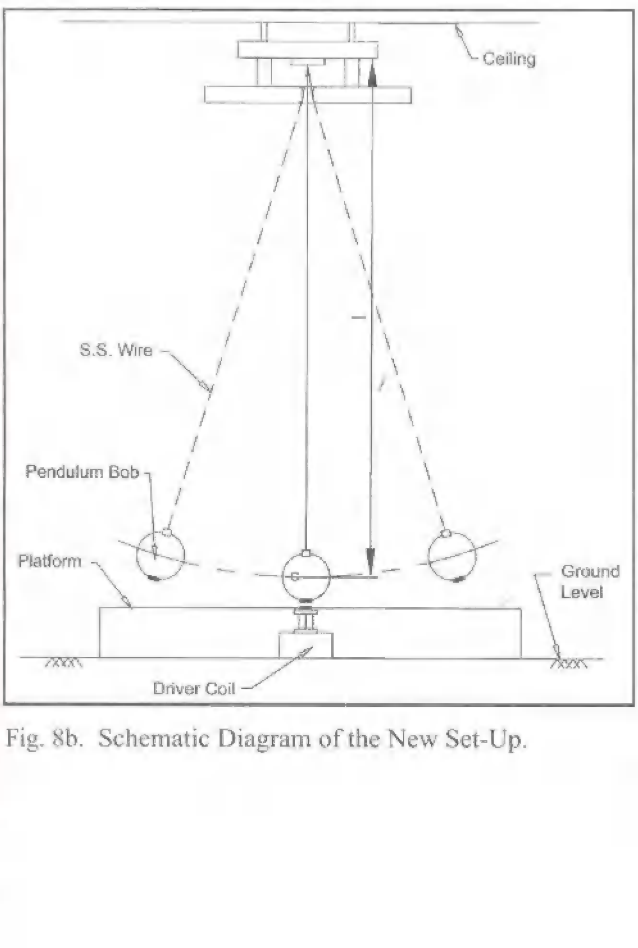

Fig. 8b. Schematic Diagram of the New Set-Up.

The New Suspension System

All the components of the new set-up were machined with great care in our workshop in order to ensure maximum possible dimensional accuracy of the fabricated parts. The suspension system comprised of two stainless steel plates of non-magnetic grade (IS 304) held exactly parallel to each other by means of three accurately machined dowel spacers 120° apart. The upper plate or the mounting plate (part no.2) of thickness 12 mm had a central undercut at its bottom surface for locating the brass housing (part no.4) for the wire die which was fitted exactly at the centre of the housing as shown in the diagram. The flared end of the die was kept on the bottom side to allow the pendulum wire wrap on its smooth surface at the two extremities of its swing. The brass housing in turn was secured to the bottom surface of the upper plate by means of three tap screws driven from the top of the mounting plate. The lower plate (or the Charron ring plate) (part no.1a) of thickness 16 mm had a central hole through which the wire was taken down. The diameter of this hole was to be such that the swinging wire of the pendulum, for the designed amplitude, would just touch the rim at the two extremities and thereby would prevent, due to frictional damping, any tendency to ellipse. In effect, the hole would then behave as the Charron ring (see Fig. 8b). The centre of this hole or the Charron ring (part no.1b) and that of the die had to be precisely in the same vertical line, so that in the still condition when the pendulum remained plumb under the weight of the bob, the wire passed exactly through the centre of the hole. This was ensured by turning the two plates together in the lathe and then centering them in the same setting of the machining operation with the holes for the dowel spacers already registered. The mounting plate was firmly held with the roof by means of three H.T foundation bolts (part no.17) again spaced 120° apart. The reason we chose to have three-point fastening for all parts of our new suspension unit was to make alignments easier. An aluminium roller with a narrow groove (part no.7) was used to slip the end of the wire over it before securing firmly with the help of the anchor bolt (part no. 9).

The Pendulum Bob

A six-inch diameter ball made of brass, which again was turned in the lathe in our workshop, served as the bob in the new set-up (part no.13). A threaded hole was made at the top of the bob, and a matching bolt with a central hole through which the lower end of the wire passed, was put inside it (part no.12b). In order to prevent the heavy bob, about 18 Kg in weight, from

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slipping off the wire under its own weight, the protruding end of the wire was bent at right angle after passing it through the hole in the fastener bolt. The bent portion being smaller than the bolt's diameter, driving the bolt down the threaded hole was no problem. A small piece of lead was put inside the hole against which the bent portion of the wire pressed as the fastener bolt was tightened and thereby prevented any possible slipping of the wire. At the bottom of the bob, exactly opposite to, and co-axial with, the centre of the fastener bolt, a thin groove was made in the bob for precisely locating a permanent ceramic disc magnet of diameter 25mm. The disc magnet was secured in place using superglue (part no.14).

We took extreme care in ensuring that no turbulence was set up in air when the bob moved to and fro; because if it did, vortices would form that might give rise to asymmetric perturbations affecting the pendulum's performance. To ensure this, the spherical surface of the bob was first finished to a high order of smoothness and then varnished. Moreover, the head of the fastener bolt (part no.11) was made round instead of being hexagonal so that the small irregularity in shape was not called upon air to play the role of the spoilsport. The round shape of the head of the bolt posed problem in tightening, which was overcome by providing suitable small holes in the rim and by making a special fastener tool for tightening.

The Driver Unit

The electromagnetic drive system we had been using for the earlier experiments basically remained the same except for the increased number of turns in the coil assembly of the new driver unit. The number of turns in the driver coil was to be increased keeping in view the heavier bob we used in the new design (Fig. 9a & 9b).

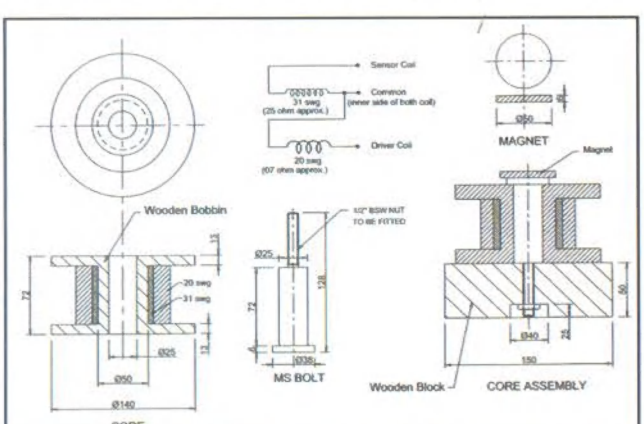


Fig. 9a. Diagram of the Driver Coil Assembly.

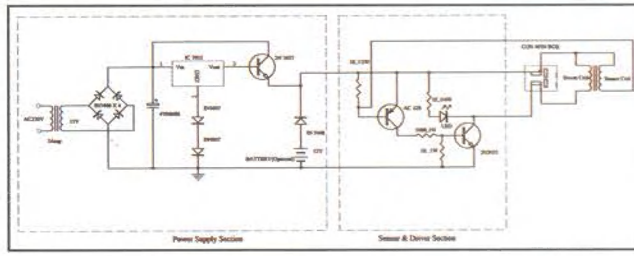


Fig. 9b. The control circuit.

The pendulum's drive system consisted of a permanent barium ferrite ceramic magnet glued to the bottom of the pendulum bob, a coil assembly (refer Fig. 9a) and a control circuit (refer Fig. 9b)). The coil assembly consisted of two concentric coils, the sensor coil and the driver coil, wound around a wooden bobbin through whose centre a soft iron rod passed. The inner coil or the sensor coil was made of 1080 turns of 31 swg super-enamelled copper wire and the outer coil or the driver coil had 1350 turns of 20 swg wire. Precautions were taken to avoid magnetic interference by the presence of ferrous material near the coil assembly.

The amplitude of swing became stable when the energy fed by the electromagnet to the pendulum system just compensated for the loss due to friction with air and at the support structure. The amplitude could be increased or decreased in our new system by decreasing or increasing the gap between the permanent magnet on the pendulum bob and the temporary electromagnet. A screw-jack mechanism (made of non-ferrous material) over which the coil assembly was kept, made this adjustment easy.

The Wire

A 16 swg stainless steel wire of the non-magnetic grade was used. Since such wires mostly come in coils, they develop a certain amount of structural bending. In order to remove the inherent bend in the wire, we had kept a length of the wire preloaded with 40kg weight for a minimum period of two months before putting it in the pendulum system.

Alignment of the system

As pointed out earlier, aligning a Foucault pendulum is a very delicate and tedious task. The centrality of the problem is to be able to achieve the following:

1) The wire, the axis of its grip (the wire-die in our system), the centre of the Charron ring, the c.g of the bob, the centre of the ceramic magnet and that of the electromagnet are to be aligned exactly along the vertical axis of the system.

2) An optimum value for the amplitude of swing is to be achieved such that the wire just touches the rim of the Charron ring rather than lapping over it and flexing beyond.

3) The portion of the wire that bends during each swing of the pendulum should, by all means, be held in perfect vertical position in the still condition. This means that the cross-section of the wire at the position of flexing should necessarily remain strictly horizontal when the pendulum is in still condition.

The beauty of our new design, as far as the question of alignment was concerned, was that it solved most of the problems by the innovative design features of the suspension system and by the very rigorous and accurate fabrication standard followed. Even before the installation, problems 1 & 3 above were mostly solved by making the suspension plate and the Charron ring plate parallel, and this was made possible by the integration of the Charron ring unit into the suspension unit- a unique feature by itself. This feature ensured that if one could successfully align the suspension plate exactly horizontal, then the centre of the Charron ring and the plumbed wire would fall exactly along the vertical through them should the wire-die be assumed to be housed perpendicular to the suspension plate by virtue of the precision in fabrication of the plate and the die housing.

Performance of the New Pendulum

The theoretical value of the pendulum's expected angular rotational rate at Kolkata (latitude 22°N) was calculated to be 5.8 degrees/hour using equation (9).

Observations were made and readings noted on hourly basis. A plot of angular displacement of the pendulum's plane against time was made for each day. The slope of the plot yielded the angular rate of rotation, which came out to be remarkably close to the theoretical value (Fig. 10). Our new pendulum missed the theoretical value by just 2 to 5 percent, whereas an error of up to 15 percent is considered acceptable world over. The performance was excellent by international standard.

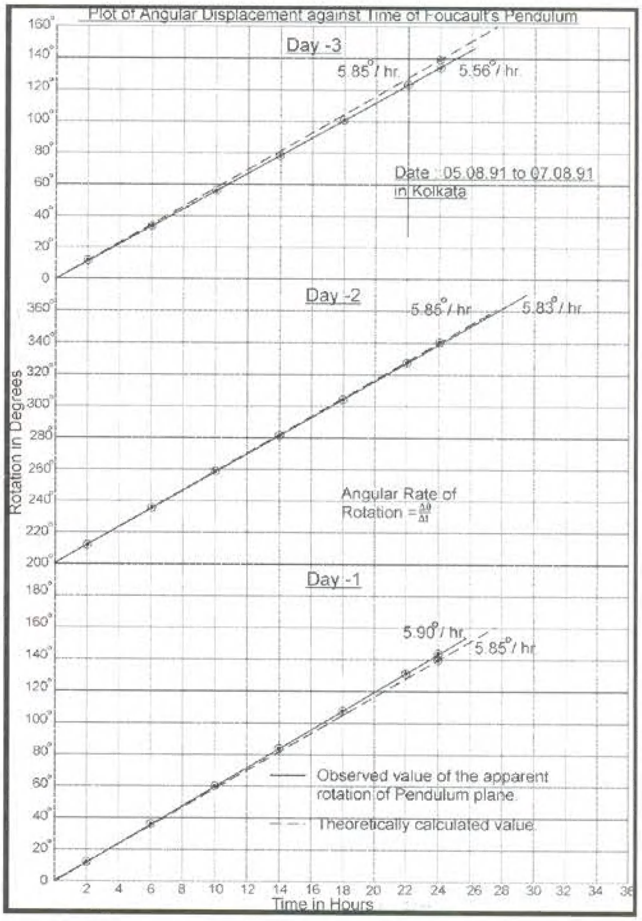
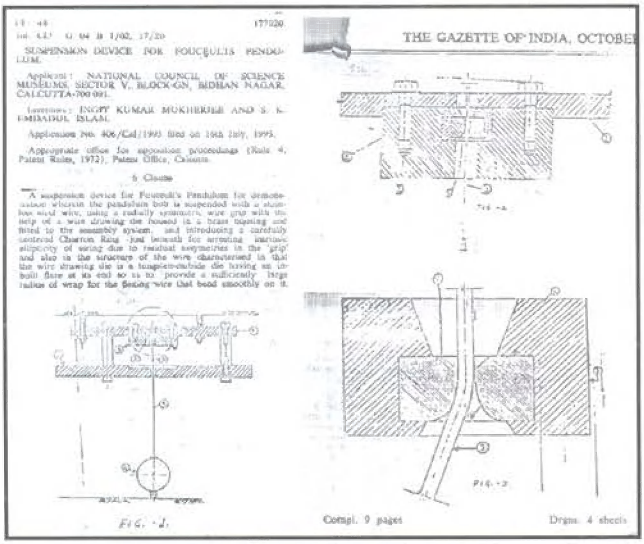


Fig. 10. Plot of Angular Displacement against Time.

Novelty of the New Design

The suspension unit of the pendulum had a few novel aspects: a wire-die as the new grip for the wire and integration of the Charron Ring with the pendulum's suspension unit.

These features of the new design were original contributions and hence merited a patent coverage. The patent had since been granted. A copy of the Gazette Notification in this regard is reproduced below (Fig. 11).



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SUSPENSION DEVICE FOR FOUCAULTS PENDULUM.

Applicant: NATIONAL COUNCIL OF SCIENCE MUSEUMS, SECTOR V, BLOCK-GN, BIDHAN NAGAR, CALCUTTA-700 091.

Inventors: INDIT KUMAR MUKHERJEE AND S. K. EMDADUL ISLAM.

Appropriate office for opposition proceedings (Rule 4, Patent Rules, 1972), Patent Office, Calcutta.

THE GAZETTE OF INDIA, OCTOBE

Compl. 9 pages

Drgs. 4 sheets

Fig. 11. Copy of Patent Gazette Notification.

Installation Sites

India's first successful Foucault pendulum for public display came into being in the year 1993 at IUCAA, Pune.

(Prof. Narlikar (5^{th} from left) & his colleagues with the author and his colleague from NCSM watching the pendulum after installation).

Fig. 12. Foucault pendulum at IUCAA, Pune.

The success of the first installation brought a series of requests from many other scientific institutions and universities. The pendulum has since been installed in the following places besides Pune.

- Queensland Science Museum, Brisbane.
- Physical Research Laboratory, Ahmedabad.
- Regional Science Centre, Tirupati.
- DDU Gorakhpur University, Gorakhpur, U.P.
- Saha Institute of Nuclear Physics, Kolkata.
- TIFAC building, IIT, New Delhi.
- ONGC Golden Jubilee Museum, Dehradun.
- Istanbul, Turkey.

Our first two pendulum installations at IUCAA, Pune and Queensland Science Museum in Brisbane provided interesting contrast.

As was expected from theory, the pendulum at Pune (18°31'N) apparently turned 4.86° per hour clockwise, while in Brisbane (27°30'S) it turned 6.92° per hour anti-clockwise. The success of our new design was thus unmistakably established by experimental results from both the hemispheres.

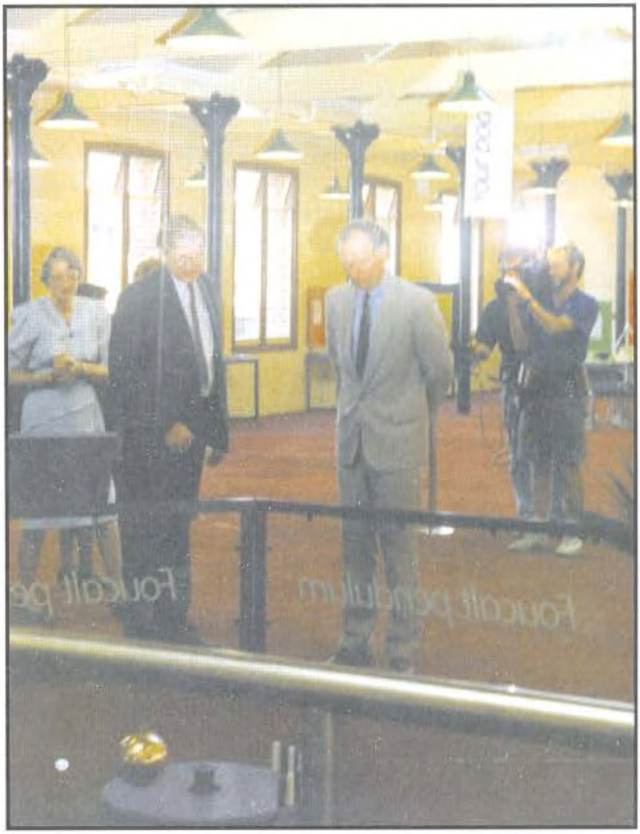

Fig. 13. Foucault Pendulum installed at Queensland Science Museum, Brisbane.

Select Readings:

1. Strong, C.L., *How to make a Foucault pendulum for corridor demonstration*, The Amateur Scientist, Scientific American, June, 1958, p.115-124.
2. Strong, C.L., *How to photograph air currents in colour and build an accurate Foucault pendulum*, The Amateur Scientist, Scientific American, Feb. 1964, vol. 210. p.132-139.
3. Somerveille, W.B., Quarterly Journal of the Royal Astronomical Society (1972) ; vol.13, p. 40-62.
4. Longden, A.C., *On the Irregularities of Motion of the Foucault pendulum*, Physical Review 13, p. 241–258 (1919).
5. Crane, Richard H., *Short Foucault Pendulum: A way to eliminate the precession due to ellipticity*, American Journal of Physics, vol.49, p.1004-1006.
6. Weltner, Klaus., *A new model of the Foucault pendulum*, American Journal of Physics, April 1979, vol. 47, p. 365-366.
7. E.O. Schulz-DuBois, *Foucault Pendulum Experiment by Kamerlingh Onnes and Degenerate Perturbation Theory*, American Journal of Physics (1970), vol.38, p. 173-188.
8. Mastner, G., Vokurka, V., Maschek, M., Vogt. E., Kaufmann, H.P., *Foucault Pendulum with eddy current damping of the elliptical motion*, Review of Scientific Instruments, 55, 1533 (1984); doi:10.1063/1.1137615 (6 pages).
9. Moppert, C.F., Bonwick, W.J., *The New Foucault pendulum at Monash University,* Quarterly Journal of the Royal Astronomical Society, 1980, vol. 21, p. 108-118.
10. Crane, H. Richard., *The Foucault Pendulum As a Murder Weapon and a physicist's Delight*. The Physics Teacher, 28(5), p.264-269.
11. Peterson, Richard. P., *A modified Foucault pendulum for a corridor exhibit*, American Journal of Physics, Aug. 1986, vol. 54, no. 8, p. 759 -761.
12. Mackay, R. Stuart, *Sustained Foucault pendulums*, American Journal of Physics, 1953, vol. 21(3), p. 180 -183 & 260-266.
13. Wallace A. Hilton, *The Foucault pendulum: A corridor demonstration*, American Journal of Physics 46(4), p. 436-438 (1978).
14. Byron E. Leonard, *A short Foucault pendulum for corridor display; Apparatus for teaching physics*, The Physics Teacher, September 1981, p. 421-423.
15. Manfred Euler and Gert Braune, *Hands-on Earth rotation*, TPT 40, 432-436 (2002).

E Islam, is Director of Birla Industrial and Technological Museum, Kolkata.